UNPLUG WITH

WAVE

Wireless Advanced Vehicle Electrification

Project ID: elt240

Wireless Extreme Fast Charging for Electric Trucks (WXFC-Trucks)

Principal Investigator, Michael Masquelier

Wireless Advanced Vehicle Electrification

June 04, 2019

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL Company

UtahState University

Schneider Electric

Cummins

THE PORT OF LOS ANGELES

TTSI

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WXFC-Trucks | Overview

Timeline

- Project start date: August 2018
- Project end date: June 2022
- Percent complete: 35%

Budget

- Total project funding: $9,838,240
  - DOE share: $4,292,137
  - Contractor Share: $5,546,103
- Funding for FY 2019: $1,249,762
- Funding for FY 2020: In-Progress

Barriers

- Meeting the window of time to deliver a medium voltage feed to the charge site
- Obtaining the necessary permits for the project
- Acclimating drivers to electric vehicles requires changing driver habits (or other personnel) for plugging in the vehicles and aligning the trucks over the wireless chargers

Partners

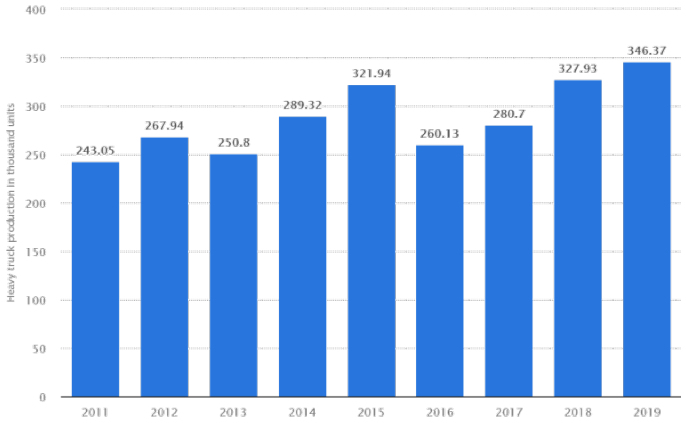
- WAVE, Inc. – Project Lead
- Cummins Inc. (Cummins)
- Schneider Electric (Schneider)
- Utah State University (USU)
- Port of Los Angeles (POLA)
- Total Transportation Services Inc. (TTSI)
- Southern California Edison (SCE)

WXFC-Trucks | Relevance

Impact

- The California Air Resource Board shows that 41% of all greenhouse gas emissions (429.5 $MMTCO_2e$ in California in 2016) is due to transportation
- 7.8% of all greenhouse gas emissions were from heavy duty trucks
- Enabler for this major pollution transportation sector to become all-electric
  - Fully charged vehicles in roughly 20-minutes means minimal down time to refuel and minimal impact on existing route planning
  - No cables means hands-free instant start of charging with no special personnel required
- Overcoming the charging time obstacle leads to a 3x to 4x reduction in actual fuel costs for vehicle operation
- Accelerate manufacturing and deployment of electric heavy-duty trucks

Heavy-Duty Truck Production in the US from 2011-2019



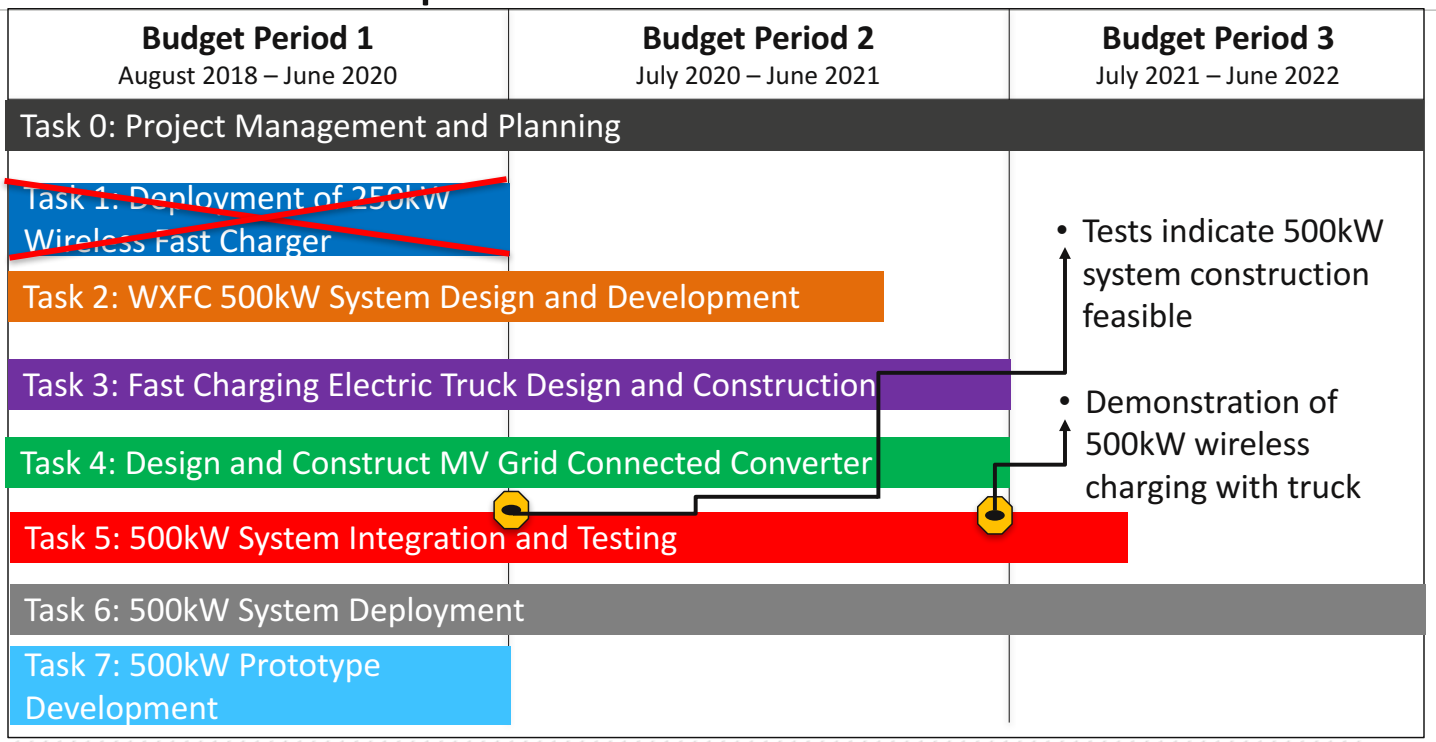
Objectives

- Wireless extreme fast charging
- MV grid to DC converter
- Extreme fast charging capable electric truck

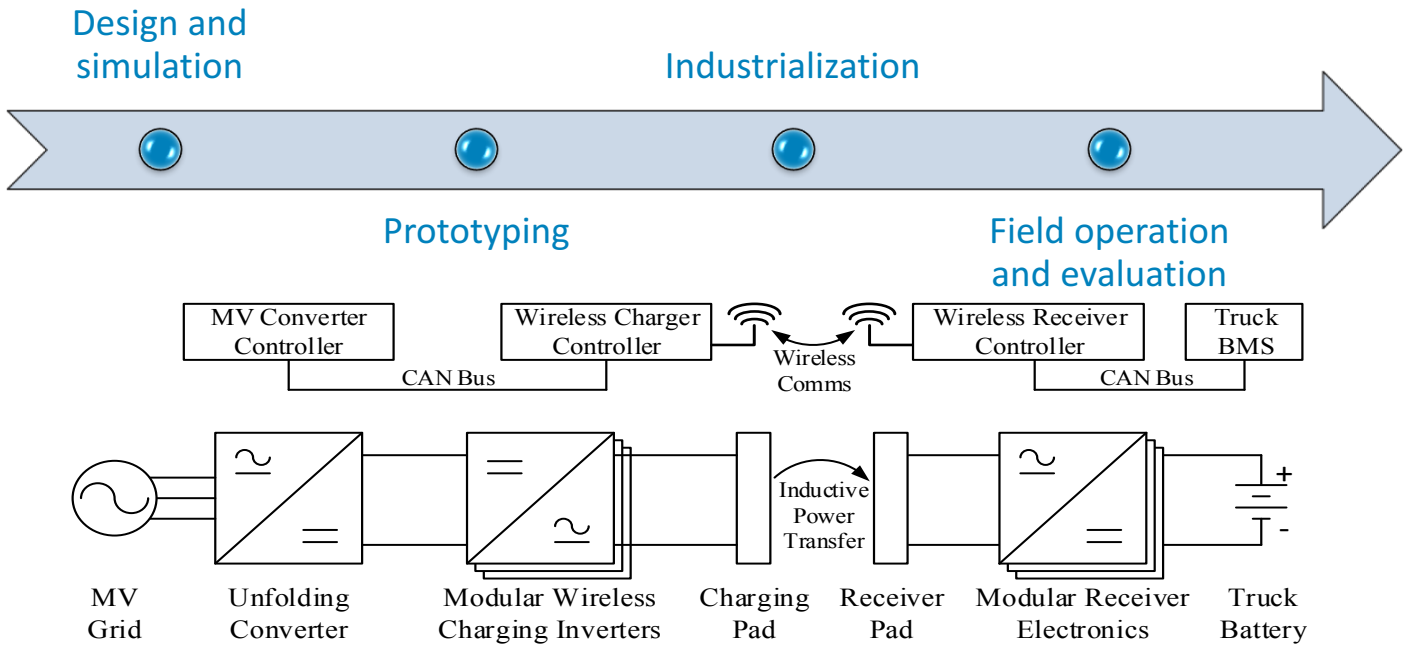
WXFC-Trucks | Relevance

FOA Objective	WXFC-Truck Expected Outcomes
Recharge battery in half the time	• New system with 500 kW wireless charging
Develop and verify vehicles equipped with XFC, charger installation and demonstration	• W-XFC system deployment and operation at POLA with two Class-8 trucks customized to support XFC. • Deployment in two stages. First early 500kW prototype charging and second final deployment at 500 kW • Combined, over two years of evaluation data and best practices
System design and grid infrastructure impact	• Direct MV 3-phase AC to DC single stage conversion solution to reduce grid integration costs, system size and weight, and improve efficiency.
Catalyze manufacturing and adoption of electric trucks	• Project goal targets key barrier to market adoption • Over two years of system hardware demonstration and evaluation are performed at one of the world's highest volume shipping ports at a critical time with zero emission requirements in place by 2035

WXFC-Trucks | Milestones



WXFC-Trucks | Approach



Block diagram of the WXFC system from MV grid to truck battery.

WXFC-Trucks | Approach

500kW MV Grid Connected AC/DC Supply Approach

- 3-phase unfolder with a soft DC bus two-level output
- Develop the 3-phase unfolder to achieve direct MV grid connection with switches commutating at the line frequency
- Design the series stacked isolated DC/DC converters to achieve the voltage step down function from MV naturally with near unity conversion ratio to obtain high efficiency

Extreme Fast Charging Capable Electric Truck Approach

- Investigate appropriate battery chemistry (LTO cells or NMC cells)
- Design custom thermal management for the cell to facilitate charging at 3C
- Select appropriate battery pack capacity and cell chemistry to integrate with electric powertrain applicable to Class 8 drayage applications

WXFC-Trucks | Approach

500kW Wireless Charging System Approach

- Leverage deployment experience with 250kW charger
- Use deployment experience to develop 500kW Prototype
- WAVE has experience integrating with different OEMs

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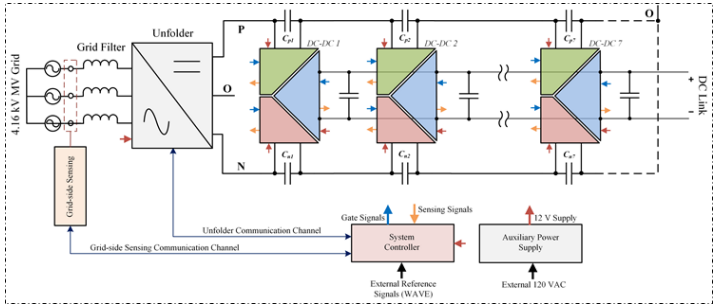
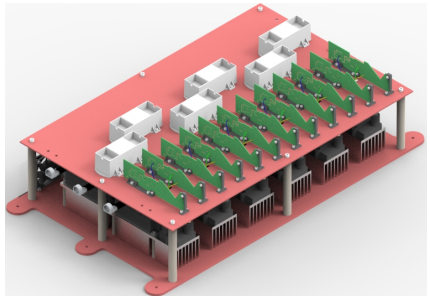
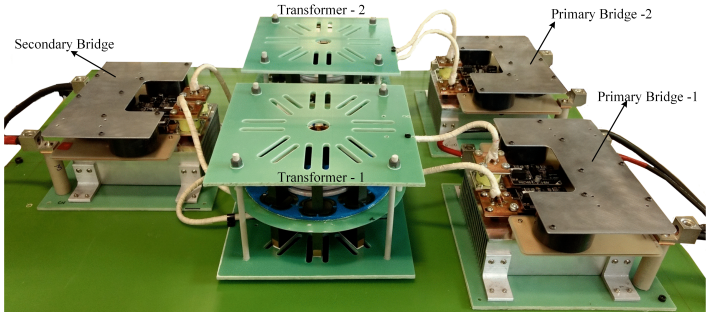
WXFC-Trucks | Technical Accomplishments & Progress

560 kW MV Grid Connected AC/DC Supply Progress

- Developed one of the seven 85 kW DC-DC converter modules and sub-components tested up to full power operation
- Developed EMI measurement setup to evaluate CM & DM conducted emissions
- Designed the 560 kW, 4.16 kV 3-phase Unfolder and started construction
- Proposed a control strategy for the series-stacking of seven DC-DC modules



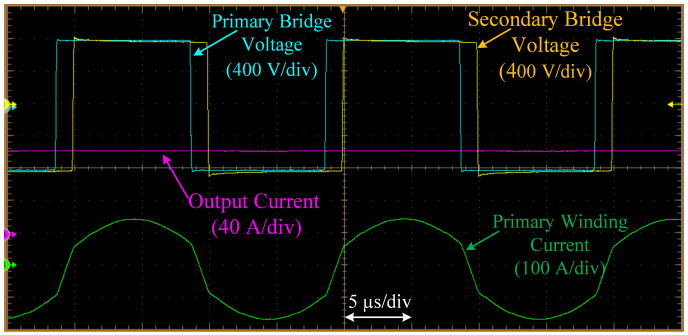




WXFC-Trucks | Technical Accomplishments & Progress

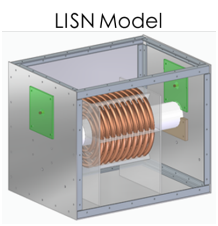
DC-DC Power Loop Test Results:

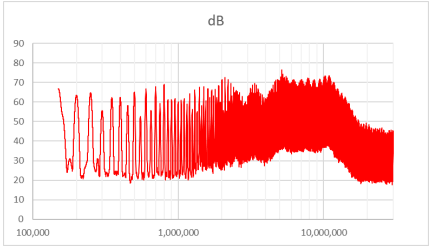
- 85 kW power test on Dual Active Bridge configuration performed
- Test validated the design of transformer and H-bridge under rated power electrical stress condition
- 98.6 % efficiency is measured at 85 kW output



EMI Testing Setup and Initial Results:

- Fabricated two FCC Part 15 50 mH LISNs
- Developed Signal splitter to distinguish common-mode and differential-mode emissions
- EMI test setup with LISNs, signal separator, and spectrum analyzer complete and initial results have been received





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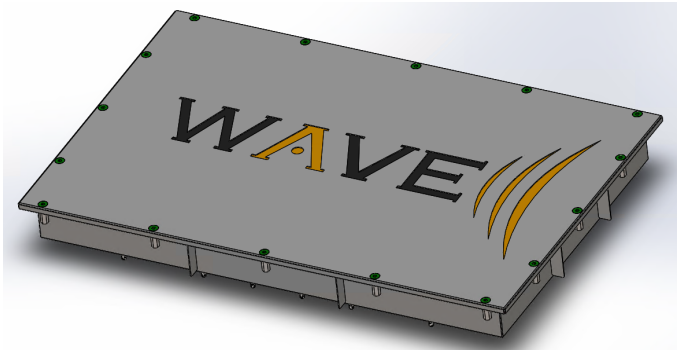
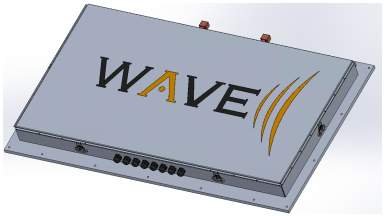
WXFC-Trucks | Technical Accomplishments & Progress

WAVE System Design Process

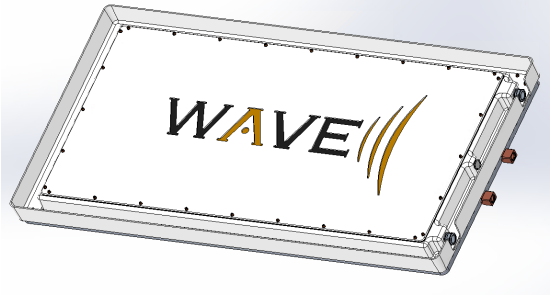
- WAVE has continued work on the extreme fast charger at 500kW with a focus on magnetics.
- Modular design approach will allow WAVE to deploy 2 X 250kW assemblies
- WAVE to meet weight, cooling requirements, and magnetic performance



WAVE 250kW Ground Side Pad



WAVE 500kW Rectifier



WAVE 250kW Receiver Pad

WAVE System Design Process

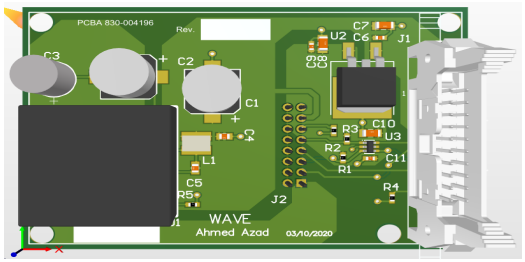
- WAVE adopting current assembly and manufacturing techniques with 500kW design.
- Serviceability and multi-configurations have been implemented into the equipment.
- Product structure has been completed

WXFC-Trucks | Technical Accomplishments & Progress

WAVE System Design Process

- Wide- bandgap SiC devices: Potential to improve XFC design and efficiency features
- Next-generation SiC switches:
  - *Lower loss*
  - *High-frequency operation capability*
  - *Reduced thermal management*

- Handful of device manufacturers explored (Cree, Rohm etc.)
- Lab characterization with WPT operating conditions required
- Passive SiC modules are being evaluated in lab with a 250kW charger



SiC- control adapter board

- System modifications carried out for smoother transition into SiC MOSFETS
- 35% reduced loss projected: Evaluation is underway
- SiC MOSFETs, driver parts are ordered
- SiC-control adapter board designed and sent for fabrication

WXFC-Trucks | Technical Accomplishments & Progress

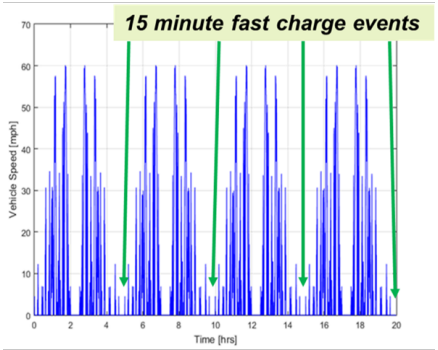
Truck requirements

- Class 8 day cab based on TTSI's requirements
- Battery selected which supports 3C charging

Key vehicle metrics	Target	As designed
Vehicle speed on 6% grade @ 82k lb GCVW	> 30 mph	32 mph
Charge power (20 minutes)	495 kW	495 kW
Tractor weight	≤ 22.5k lb	23.0k lb
Vehicle range	> 45 miles	58 miles
Work day duty cycle	20 hours 160 miles	20 hours 200 miles

Truck status

- Design complete for Kenworth T680 day cab battery electric truck integrated with WAVE secondary charging plates and rectifier
- Truck #1 build is 90% complete
- Truck commissioning to begin in June
- Stand alone battery test impacted by COVID-19
  - Expected completion now July

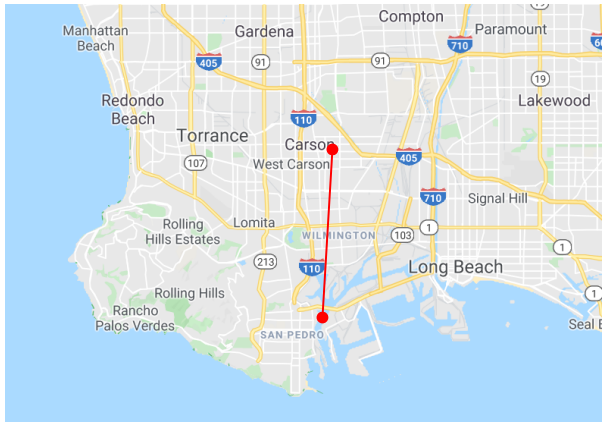


WXFC-Trucks | Technical Accomplishments & Progress

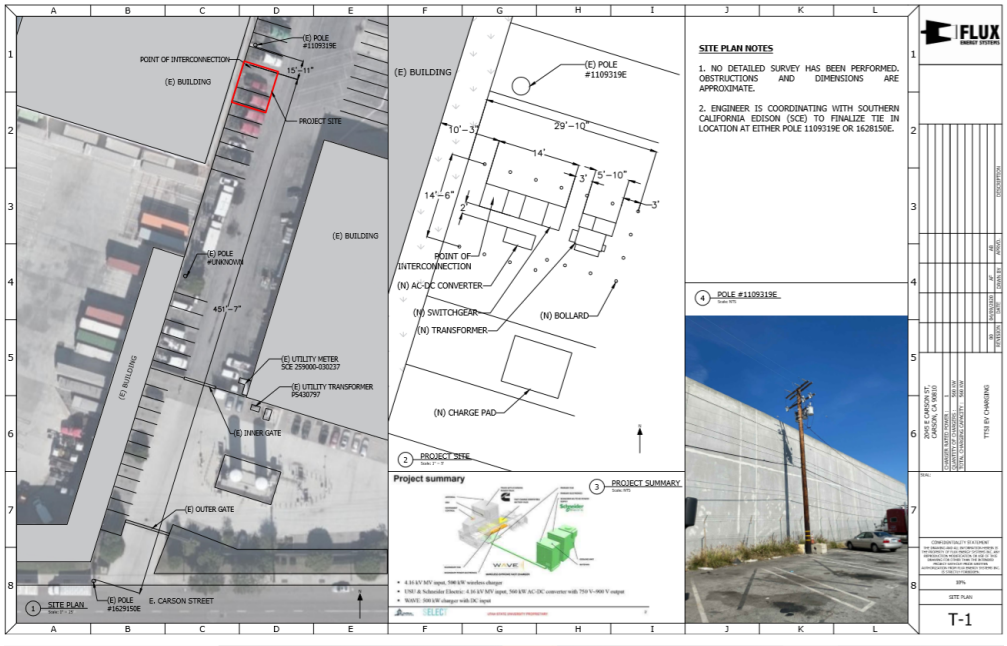
Update

Pivot to Carson Location

- Change in primary service voltage
- Exploring SCE Charge Ready Program eligibility



Updated Site Plan

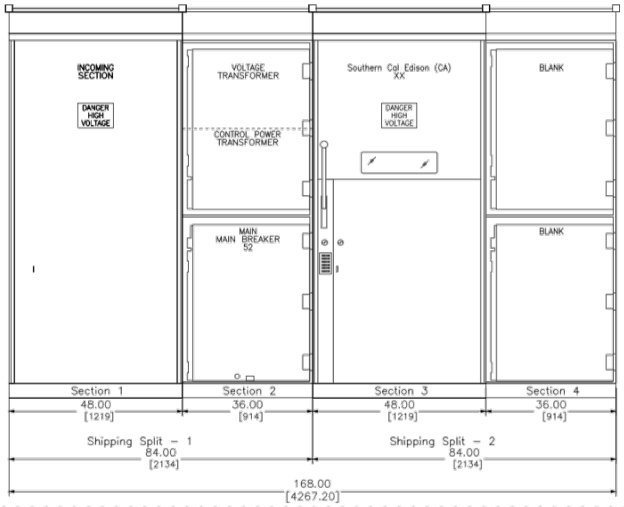


WXFC-Trucks | Technical Accomplishments & Progress

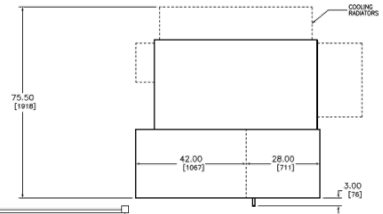
Modifications to plan

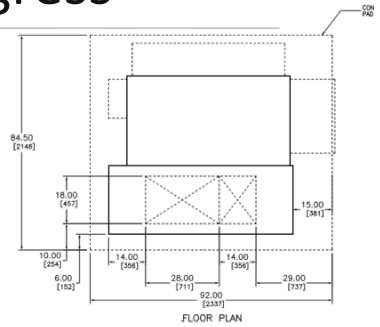
- Change to ULSE Meter/Main Switchgear
  - 4160v to 12,000v
  - LADWP to SCE interconnect requirements
- Addition of a step-down pad mounted transformer in lieu of changing power electronics design
  - Advantage in time savings
  - Additional cost

New Switchgear Layout



TOP VIEW





FLOOR PLAN

Additional Transformer Footprint Requirement

WXFC-Trucks | Response to Previous Reviewer Comments

Approach:
Reviewer: "The approach addresses both the technical aspects of the charger design and the practical aspects of its deployment."
Response: The project runs the full spectrum from concept, simulation, design, prototype, vehicle integration, full product deployment, & real-world goods movement in CA.

Technical Accomplishments & Progress:
Reviewer: *"After the first year of the 3+ year program, only 10% of the full effort is complete."*
Response: Now estimate 35% complete for overall project. 1st truck ready in Q3, wireless charger design completed, charger site plan close to completion. On track for successful field demonstration.

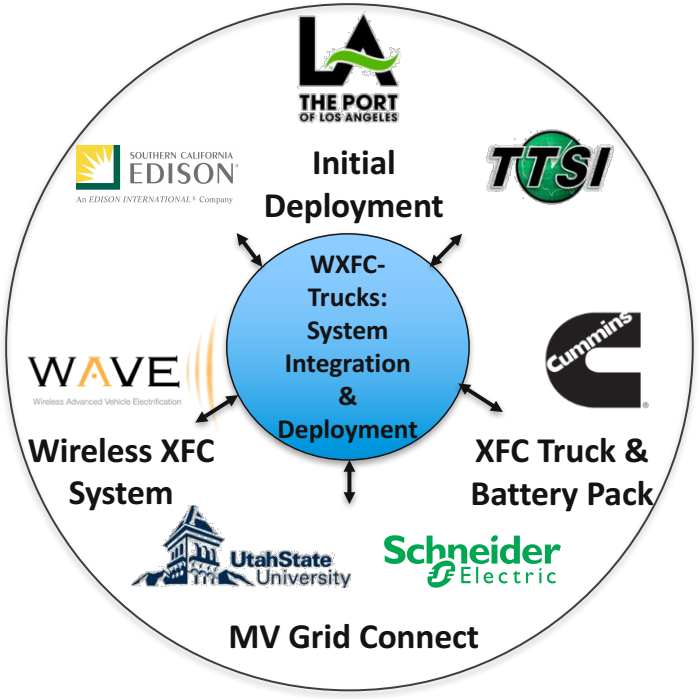
Collaboration & Coordination Across Project Team:
Reviewer: *"This project has the right partners in the right areas to make this a successful project; the team just needs to execute."*
Response: Strong, frequent, structured communication exists amongst all team members (WAVE, Cummins, USU, Schneider Electric, TTSI, SCE), which has led to increased progress.

Proposed Future Research:
Reviewer: *"If successful in the future work, this will pave the way to new applications of electrification in this space. Good execution of this future work is critical."*
Response: This effort is happening in parallel with other wireless charging projects at Port of LA, including Class-8 yard trucks and 52-ton container handlers.

Relevance:
Reviewer: *"This is the first project that goes from charger design to site deployment, thereby demonstrating the practical reality of this technology leading to its adoption."*
Response: This effort has already spawned discussions with TTSI about additional 500kW chargers and E-Trucks at additional sites.

Resources:
Reviewer: *"Given the level of funds for Year 1 and percent complete of 10%, funds for the first budget period seem high, however for the overall project they seem appropriate."*
Response: Resources have been consistently added from each team. Also, project scope is very broad and there is much front-end loaded effort to realize the final end demonstration.

WXFC-Trucks | Collaboration & Coordination with Other Institutions



- **The Port of Los Angeles** – Deployment Partner
- **Southern California Edison** – Deployment Partner
- **Total Transportation Services Inc.** – Port Trucks Partner
- **Cummins** – Truck Integration and Electric Drivetrain Partner
- **Utah State University** – Research Partner
- **Schneider Electric** – Electrical Supplier, Industrialization Partner

WXFC-Trucks |Remaining Challenges & Barriers

MV-Grid Converter:

- Optimized control strategy for the DC-DC modules series stacking control
- Confirm converter layout, design and communication satisfy the MV related high voltage isolation requirements from UL field evaluation
- 500 kW full power test of the AC-DC converter

WAVE System Design & Process:

- Effective cooling to reduce hot spotting and thermal runaway scenarios
- Ideal ferrite placement to avoid saturation
- Manufacturing process for actively cooled wire
- Control leakage to surrounding environment

Truck Design:

- Ensuring adequate thermal management of battery and WAVE components during charging under range of environmental conditions

WXFC-Trucks |Proposed Future Research

Future Research Opportunities:

- Battery: To improve long-term commercial viability, industry needs to develop a low-cost, higher energy density 3C charge (continuous) capable battery
- Grid Feed: Optimize MV-to-DC Converter for various electric utility MV voltages available.
- Thermal: Minimization of heat generated and novel thermal materials.
- Operator Cost: Addition of stationary storage to offset demand and TOU charges.
- System: Overall improved system-level efficiency.

Any proposed future work is subject to change based on funding levels

WXFC-Trucks |Summary

This project brings together all three critical components needed to solve the barrier for adoption of electric heavy-duty vehicles:

- High-efficiency MV grid supply to lower energy costs and reduce total footprint of equipment
- High-efficiency, high-energy density wireless extreme fast charger
- An all-electric vehicle capable of high C-rate charging and equipped to handle a wireless charging system

This project's overall system approach is driving research that will result in a highly cost-effective solution that will make adoption of all-electric fleets not only viable, but very compelling.

Critical success factors include:

- Development of a 500kW wireless charging system
- Development of a Class-8 truck powertrain with a battery pack capable of reliably and repeatedly charging at a greater than 3C-rate up to 500kW
- Development of a modular direct MV 3-phase AC to DC power converter
- Achieve system MV grid to vehicle battery efficiency of 92%